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REPORT No. 580 c.3

HEAT TRANSFER TO FUEL SPRAYS INJECTED INTO HEATED GASES

By ROBERT F. SELDEN and ROBERT C. SPENCER

1937

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$-sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of $c.p.$ from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By ROBERT F. SELDEN and ROBERT C. SPENCER
Langley Memorial Aeronautical Laboratory

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REPORT No. 580

HEAT TRANSFER TO FUEL SPRAYS INJECTED INTO HEATED GASES

By Robert F. Selden and Robert C. Spencer

SUMMARY

A study has been made of the influence of several variables on the pressure decrease accompanying injection of a relatively cool liquid into a heated compressed gas. Indirectly, this pressure decrease and the time rate of change of it are indicative of the total heat transferred as well as of the rate of heat transfer between the gas and the injected liquid. Air, nitrogen, and carbon dioxide were used as ambient gases; Diesel fuel and benzene were the injected liquids. The gas densities and gas-fuel ratios covered approximately the range used in compression-ignition engines. The gas temperatures ranged from 150° C. to 350° C.

Several general conclusions may be drawn from the experimental results: Vaporization begins immediately after the start of injection; the initial rate of heat transfer is a direct function of the initial temperature difference between the gas and the fuel; and the heat transfer is less efficient the greater the injected fuel quantity, even though the total heat transferred is greater.

INTRODUCTION

It is generally recognized that the compression-ignition engine in its present state of development suffers the disadvantage of inefficient utilization of its air charge. Recognizing that the utilization of the air must be partly dependent upon the fuel spray, Lee has conducted a detailed photographic investigation of the exterior characteristics of fuel sprays (reference 1). He has also determined the spatial distribution of the fuel within the spray (reference 2). These spray investigations have been extended by tests with the N. A. C. A. combustion apparatus and the results give an improved insight into the gross physical and chemical processes as they occur in the engine. (See references 3 and 4.)

The ignition lag in compression-ignition engines has been shown to influence the character of the subsequent explosion (references 5 and 6). No entirely satisfactory explanation of this fact has been given, but certain general conclusions can be drawn: In general, the fuel must be heated after injection; the fuel and the air must be mixed; and certain preliminary chemical reactions must take place before the actual ignition can occur. The observed lag is thus a composite of the intervals associated with these processes. It follows that heating the fuel prior to injection cannot reduce the ignition lag indefinitely although some reduction may be accomplished in this manner (reference 7). Rothrock and Waldron have shown that appreciable vaporization follows injection of the fuel into the combustion apparatus (reference 8). The time required for this vaporization to begin was not established but, in view of Wentzel's theoretical analysis of the heating and vaporization of fuel droplets suspended in a heated gas (reference 9), there is every reason to believe that appreciable vaporization occurs in a compression-ignition engine during the ignition-lag period.

The present investigation was undertaken to isolate the heat transfer accompanying the mixing of a fuel spray and the ambient gas in a bomb and to study the influence of several variables on this individual process. The results of this investigation should give an insight into the time required to effect some vaporization since this process necessarily corresponds to a portion of the total heat transfer. Experimentally, heat transfer is not directly measurable in a system of this type; therefore, resort has been had to an indirect approach, namely, the measurement of the change in pressure accompanying the adiabatic exchange of heat between the gas and fuel after injection of the latter into a bomb. The primary variables were the gas temperature, the gas density, and the gas-fuel ratio. The effects of the nozzle design, the fuel temperature, the kind of fuel, and the character of the ambient gas were less extensively investigated.

Gas densities covering most of the range found in engine practice were used. For mechanical reasons temperatures corresponding to those attained in compression-ignition engines at top center could not be used. The maximum temperature employed was actually somewhat less than that of the gas charge prevailing at the start of injection (references 10 and 11) in compression-ignition engines.

ANALYSIS OF THE PROBLEM

The transfer of heat to a suspended droplet can take place by two mechanisms: conduction and radiation. Except insofar as their boundary conditions are altered, the mass flow of gas, induced by the injection of the liquid fuel, presumably is of little importance with respect to the individual droplets because of their low relative velocity (reference 12). The situation may be

vastly different, however, for the spray considered as a unit, particularly for injection into an engine having induced air flow. Radiation to the surfaces of the droplets takes place to some extent and, whereas the actual magnitude of this exchange is uncertain, the maximum rate for energy transferred in this manner can be estimated for comparative purposes.

For conductive heat transfer there are two controlling resistances: The first is within the droplet itself and the second must be associated with the equivalent of a film surrounding the droplet. The first can be analytically treated but the second presents difficulties. Because of the net transfer of molecules from the droplet surface, the character of this film is not independent of time, as is usually assumed in theoretical treatments. (See references 9, 13, 14, and 15.) In fuel sprays the vapor films about the liquid droplets probably interpenetrate, thus necessitating some consideration of the spray as a whole. Moreover, the fuel is not uniformly distributed within the spray. In view of these difficulties no attempt will be made to establish any mathematical relations for the heat transfer through the film encompassing the droplet.

Heat transfer within a droplet.—Ingersoll and Zobel have published equations pertaining to the internal heating of a rigid sphere suddenly inserted into a fluid possessing a higher temperature (reference 16). These equations may be modified to give, respectively, the instantaneous center temperature t_c and the average temperature t_a of the droplet:

$$t_c = t_i + (t_s - t_i)\left[1 - 2\left(e^{\frac{-\pi^2 h^2 t}{R^2}} - e^{\frac{-4\pi^2 h^2 t}{R^2}} + e^{\frac{-9\pi^2 h^2 t}{R^2}} - \ldots\right)\right]$$

$$t_a = t_i + (t_s - t_i)\left[1 - \frac{6}{\pi^2}\left(e^{\frac{-\pi^2 h^2 t}{R^2}} + \frac{1}{4}e^{\frac{-4\pi^2 h^2 t}{R^2}} + \frac{1}{9}e^{\frac{-9\pi^2 h^2 t}{R^2}} + \ldots\right)\right]$$

where t_s is the temperature of the shell, ° C.
t_i, the initial droplet temperature, ° C.
R, the radius of the shell, centimeters.
t, the immersion time, seconds.
h^2, the thermal diffusivity of the liquid in the droplet.

As applied to liquid droplets these relations do not represent the effects of possible internal convection currents. These currents, if present, would increase the rate of temperature rise as determined by these relations.

It follows from these relations that when h^2 is considered constant, the increase in both the center and average temperature above the initial droplet temperature is a definite fraction of the difference $t_s - t_i$; thus $t_c - t_i = \alpha\,(t_s - t_i)$ and $t_a - t_i = \beta\,(t_s - t_i)$. The assumption of a constant value of h^2, independent of temperature in the range employed, appears justified for the purpose of qualitative comparisons in view of the uncertainty involved in its estimation. An average value for the range 49° C. to 350° C. can be estimated on the basis of the average values of the thermal conductivity (0.00027 calorie per second per centimeter per degree C., reference 17), the density (0.713 gram per cubic centimeter, reference 18), and the specific heat (0.662 calorie per gram per degree C., reference 19). These values result in $h^2 = 0.000572$ square centimeter per second.

Values of α and β are given in the following table for several immersion intervals and droplet radii, the largest radius corresponding to the initial average size (reference 20). No actual values of droplet temperatures are given inasmuch as there is no adequate basis on which to estimate their surface temperature. Incidentally, the foregoing relations tacitly assume that the surface temperature is instantaneously attained and thereafter remains constant. This assumption does not greatly invalidate the fact that the increase in the temperature of the droplet, particularly the average temperature as shown by the β values, attains a large fraction of the possible increase in a remarkably short time. Moreover, the smaller the radius the more quickly this fraction approaches unity. As a result of evaporation, the surface temperature does not attain so high a value as it would if all the heat reaching the drop served to heat it. Even so, such evaporation presumably does not alter the establishment of thermal equilibrium within the droplet and hence the α and β quantities still have significance.

HEATING RATES FOR IMMERSED SPHERES

$[t_c - t_i = \alpha(t_s - t_i);\ t_a - t_i = \beta(t_s - t_i)]$

Droplet { cm radius { in	0.0015 .00059		0.0020 .00079		0.0025 .00098	
Immersion time	α	β	α	β	α	β
Second						
0.0001	0.002	0.464	0.000	0.362	0.000	0.296
.0003	.154	.706	.018	.573	.004	.479
.0005	.444	.826	.128	.690	.024	.587
.0007	.658	.895	.296	.771	.092	.666
.0010	.838	.951	.520	.851	.344	.749
.0015	.874	.962	.760	.927	.494	.842
.0020	.986	.996	.882	.964	.674	.900

Radiation from bomb wall.—Some insight into the possible contribution of radiation from the bomb wall to the total heat transfer follows from a consideration of the maximum rate of radiation. If the very questionable assumption is made that the droplets are true black bodies suspended in a space filled with black-body radiation, the net energy transferred in calories per second is given by:

$$\Delta H = 1.37 \times 10^{-4} S\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]$$

(reference 21) where

S is the surface area of the drop.
T_1, the bomb-wall temperature, degrees K.
T_2, the droplet temperature, degrees K.

The extent to which the droplets are not black bodies introduces a factor that reduces this rate. The existence of black-body radiation within the bomb is actually the case prior to injection, but thereafter the radiation within the spray envelope undoubtedly corresponds to a lower temperature than that of the bomb walls. This fact again entails a diminution in the rate indicated by the equation. The area S may be taken as equivalent to that of the number of droplets of average size (reference 20) required for a spray of given weight.

For comparison with the observed rate of heat transfer, expressed in this case in terms of rate of pressure drop, the calculated rate of radiant transfer must be expressed in identical units. Although not indicative of the actual mechanism, this rate can be put in terms of the units in which the experimental data are expressed by considering all the radiant energy as being derived from the ambient gas.

Basic considerations of experimental method.—The observed decrease in pressure accompanied the decrease in temperature of the ambient gas caused by the flow of heat from it to the injected liquid. This process was essentially adiabatic in view of the small rate of heat transfer from the bomb wall. Cragoe's empirical relations (reference 17) for the specific and vaporization heats of oils permit the calculation of the pressure decrease that should accompany the complete vaporization of a given amount of fuel when all the heat is abstracted from the gas phase. When the total heat absorbed by the fuel in vaporizing is equated to that lost by the ambient gas, these relations lead to an expression that can be solved by trial and error to give the final equilibrium temperature:

$$t_f=\frac{NC_vt_i-49.5w}{NC_v+0.333w+0.000444wt_f}$$

where N is the moles of ambient gas.

C_v, the molal specific heat of this gas, taken as constant between t_f and t_i.

t_i, the initial gas temperature, °C.

w, the weight of injected fuel, grams.

It follows at once that the temperature drop (t_i-t_f) should remain constant for a given initial temperature and gas-fuel ratio, i. e., essentially N/w. The corresponding diminutions in the partial pressure of the gas are calculable from the expression

$$P_i-P_f=\frac{P_i(T_i-T_f)}{T_i}$$

in which P_i is the initial pressure, atmospheres.

P_f, the final pressure, atmospheres.

T_i, the initial absolute gas temperature, degrees K.

T_f, the final equilibrium gas temperature, degrees K.

This expression is strictly applicable only to the initial stage of the heat-transfer process when little vapor exists. Later in the process, however, these diminutions should be greater than the experimentally derived maximum values to the extent of the partial pressures of the vapor, these latter being directly proportional to the initial pressure for a given initial temperature and gas-fuel ratio. Thus the calculated actual drop to be expected under these stipulated conditions is in accordance with

$$(P_i-P_f)_{actual}=P_i\left[\frac{(T_i-T_f)}{T_i}-C\right]$$

where C is a correction factor necessitated by the presence of the fuel vapor. This factor is equal to the partial pressure of the vapor of the injected liquid divided by the initial gas pressure. The partial pressure was obtained from the perfect gas law and the known bomb volume, gas temperature, fuel weight for the particular gas-fuel ratio, and an estimated average molecular weight of 200 (reference 22). It follows from this expression that the pressure drop should be directly proportional to the initial pressure if the fuel derived all its heat from the gas phase under the assumed conditions of constant initial temperature and air-fuel ratio.

Some conception of the rate of heat transfer can also be obtained from the experimental results, particularly for the early part of the process in which the number of moles of gas is essentially invariant. It follows from the perfect gas law that the rate of pressure change is related to the rate of temperature change by

$$\frac{dP}{dt}=\frac{NR}{V}\frac{dT}{dt}$$

wherein R is the gas constant.

V, the volume of the bomb.

Also, the rate of change in the energy content of the gas phase must equal the rate of heat transfer, thus:

$$\frac{dQ}{dt}=C_vN\frac{dT}{dt}$$

If minor variations in C_v and N are neglected, it follows that the rate of heat transfer is proportional to the rate of pressure decrease. For the practical purpose of showing the trends in the present data it is sufficient to use these rates interchangeably as though they were synonymous.

The expression $\frac{dP}{dt}=\frac{NR}{V}\frac{dT}{dt}$ can also be used to compare the relative rates of temperature drop in different gases when the corresponding rates of pressure change are known for a given initial gas temperature, density, and gas-fuel ratio. The initial pressure under such conditions is very nearly proportional to N, hence the ratio of the initial rate of pressure drop to the initial pressure is proportional to the initial rate of temperature drop irrespective of the nature of the gas.

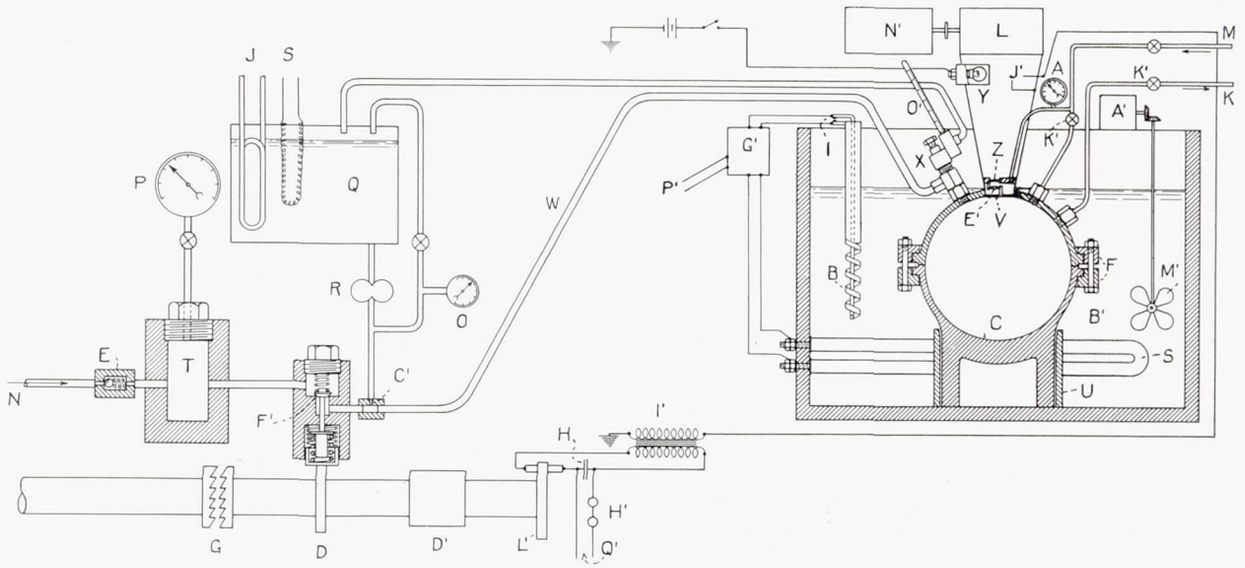
APPARATUS AND METHOD

The experimental method employed in this investigation consisted in photographically recording with a suitable indicator the decrease in pressure following the injection of a definite quantity of liquid into a spherical bomb containing a gas at a known temperature and pressure. With the exception of a few minor modifications this apparatus was essentially as described in reference 23. The present arrangement is shown diagrammatically in figure 1. The essential parts were a bomb, a constant-temperature bath, a fuel-injection system, and an optical-type differential-pressure indicator. The stainless-steel bomb has a volume of 600 cubic centimeters and is provided with openings for the injection valve, the gas inlet and exhaust fittings, and the indicator.

The liquids used in the constant-temperature bath were S. A. E. 30 lubricating oil for the low temperatures and an approximately 1:1 mixture of sodium and potassium nitrates for the high temperatures. The bath temperature was kept within $\pm 2°$ C. of the desired value by an automatic control.

The injection system delivered a single fuel charge of the desired weight upon the release of a trip mechanism. The injection valve was so constructed that fuel could be continuously circulated through it, thereby maintaining a constant fuel temperature of $49° \pm 1.5°$C. Three nozzles were used, all having equivalent orifice areas: A 13-orifice, a 2-impinging-jets, and a single-orifice nozzle with an orifice diameter of 0.050 inch (fig. 2). The fuel weights were varied by changing the injection pressures; the latter varied from about 194 to 600 atmospheres (2,850 to 9,000 pounds per square inch) for each nozzle. The requisite injection pressure for a given fuel quantity was determined just prior to a series of tests at each temperature. The injection period ranged between 0.002 and 0.006 second, depending upon the injection pressure used.

The high-pressure indicator employed in earlier work (references 6, 11, and 23) was altered to record small pressure differences by substituting a thin corrugated phosphor-bronze diaphragm for the heavy steel diaphragm and by providing a gas connection between the sealed chamber above the diaphragm and the bomb proper. The same initial pressure was applied to both sides of the diaphragm but, just before injection, a valve inserted in this connection was closed. This procedure permitted the subsequent pressure difference to actuate the indicator and thus to generate a trace of the pressure-difference variation with time on the film. This valve was opened again immediately after injection in order to minimize the interval within which the diaphragm remained deflected. A spark, recorded as a vertical line on certain records, marked the start of injection. This spark and injection start were synchronized by observing the spray with a neon-tube stroboscope actuated by the switching device on the injection system that ordinarily controlled the spark. The film drum was driven by a synchronous motor to provide the time scale.

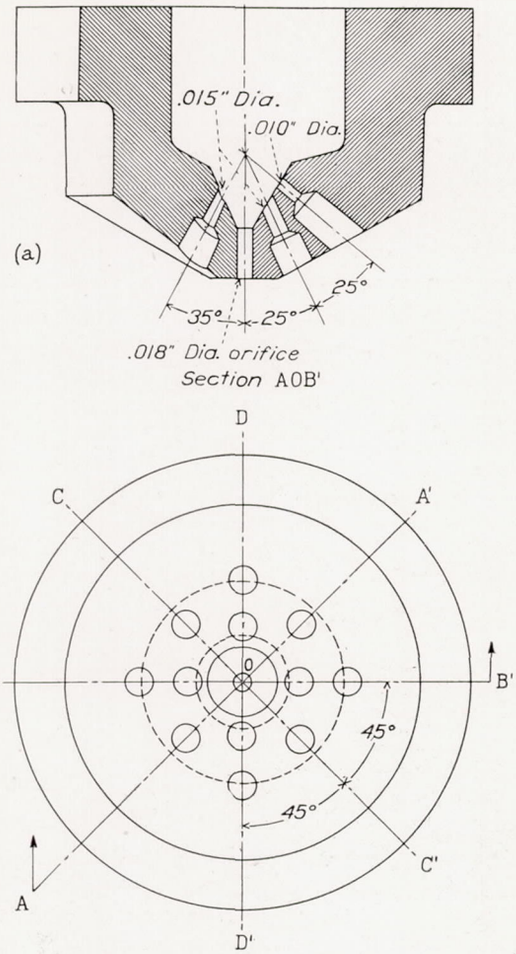


A, air gage.
B, bimetallic strip.
C, bomb.
D, cam.
E, check valve.
F, clamping rings.
G, clutch.
H, condenser, 8 microfarad.
I, contact points.
J, cooling coil.
K, exhaust.
L, film drum.
M, from compressed-gas bottle.
N, from high-pressure pump.
O, fuel-circulating pressure gage.
P, fuel high-pressure gage.
Q, fuel reservoir.
R, gear pump.
S, heating coil.
T, high-pressure reservoir.
U, holder for bomb.
V, indicator diaphragm.
W, injection tube.
X, injection valve.
Y, lamp.
Z, lens.
A′, motor.
B′, oil bath.
C′, orifice, 0.020 inch.
D′, phase-changing gears.
E′, pivoted mirror.
F′, poppet valve.
G′, relay.
H′, resistance lamps.
I′, spark coil.
J′, spark gap.
K′, quick-acting valves.
L′, spark-timing switch.
M′, stirrer.
N′, synchronous motor.
O′, thermometer.
P′, voltage 220 a. c.
Q′, voltage 230 d. c.

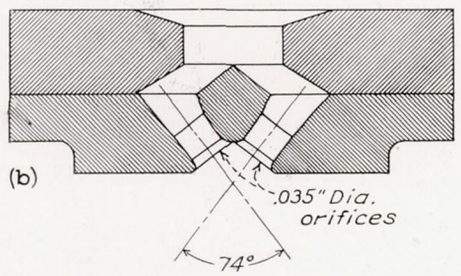
FIGURE 1.—Diagrammatic sketch of the apparatus.

Air, nitrogen, and carbon dioxide were used as ambient gases; nitrogen was substituted for air in the tests at the higher temperatures because air permitted auto-ignition of the fuel oil at 230° C. with certain gas-fuel ratios. A few tests were made with carbon dioxide because its physical characteristics were considerably different from the other two gases. The gas densities correspond to 5, 10, 15, and in some tests 20 atmospheres absolute at 100° C. All gases were considered to be ideal when computing the pressures corresponding to the several densities and temperatures. The initial gas temperatures ranged from 150° to 350° C.

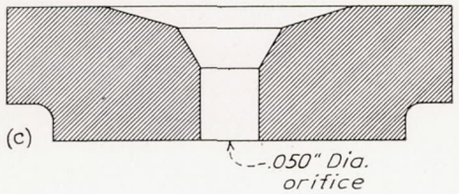
Different liquids were injected: An automotive Diesel fuel (Auto Diesel) was investigated most extensively because of its practical importance; benzene, because its critical temperature was within the available temperature range; and water, because of its large heat of vaporization. The water tests were not very extensive and, as they failed to show any interesting dissimilarities, these data have been omitted. The Diesel fuel had a viscosity of 70 and 52 Saybolt seconds Universal at 38° and 99° C. (100° and 210° F.), respectively, and a density of 0.831 gram per cubic centimeter at 15° C. Its A. S. T. M. distillation curve is given in figure 3.



(a) The 13-orifice nozzle; plane DD′ is identical with BB′, and plane CC′ is identical with AA′.



(b) The 2-impinging-jets nozzle.



(c) The single-orifice nozzle.

FIGURE 2.—Diagrammatic sketches of the three nozzles.

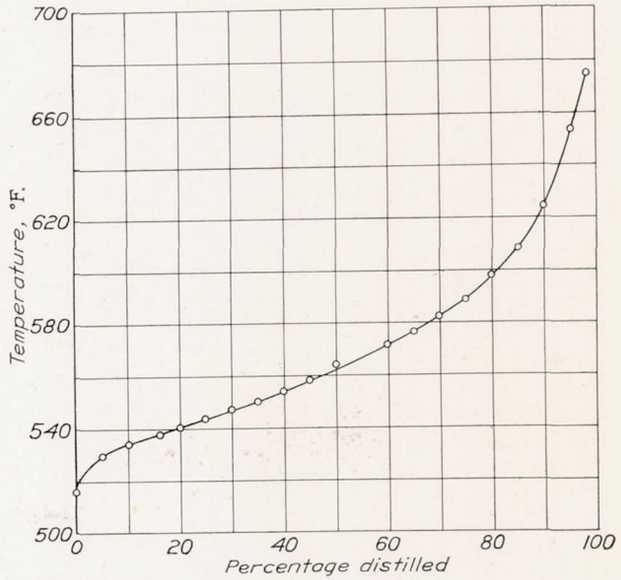


FIGURE 3.—The A. S. T. M. distillation curve for Auto Diesel fuel.

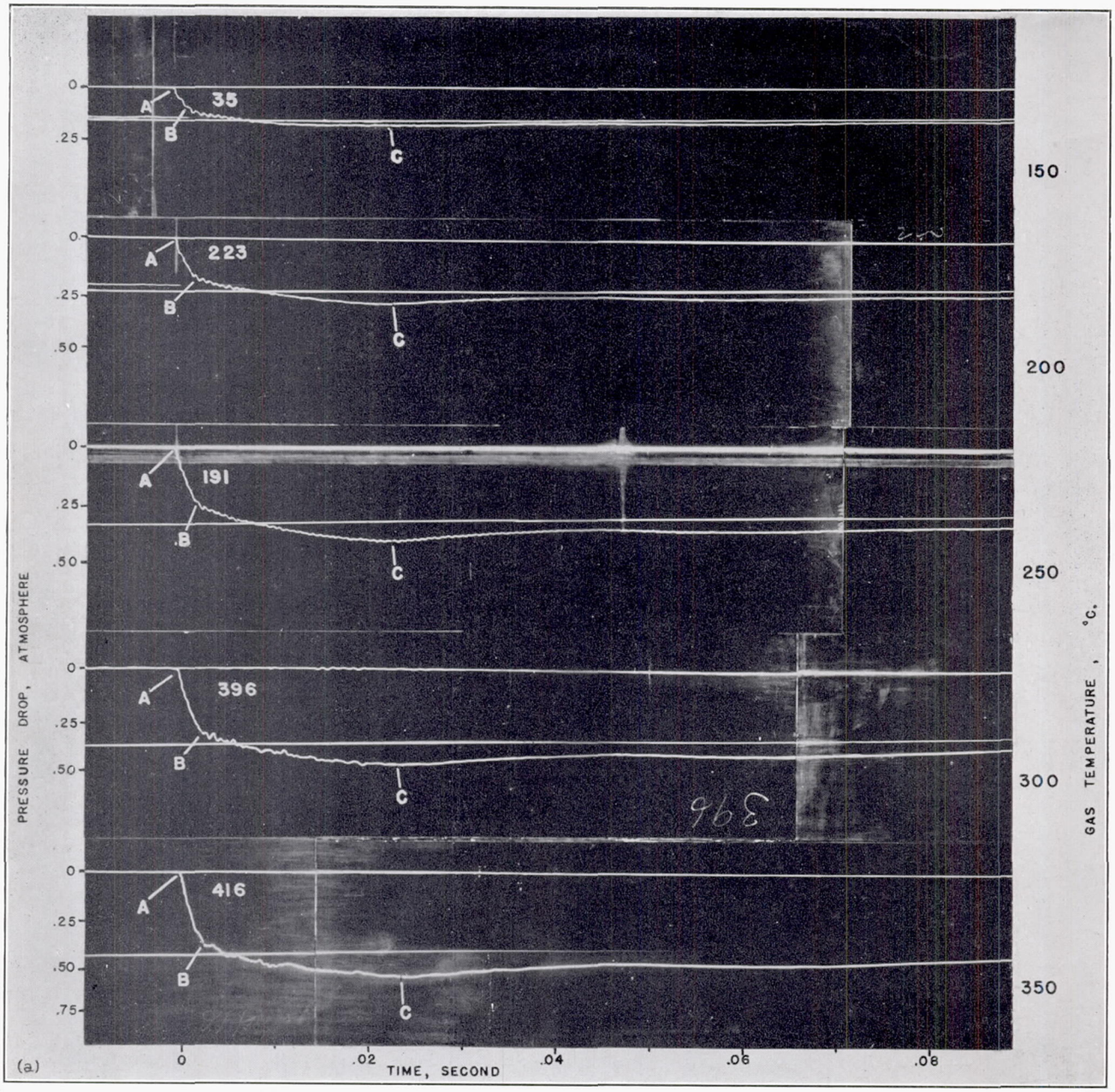
RESULTS

The data derived from the experimental records corresponding to the injection of Diesel fuel are presented in table I. Typical records for an intermediate fuel quantity (0.284 gram) and gas densities of 4.73 and 14.19 grams per liter are reproduced in figure 4. The effect of the nozzle design on the heat transfer to the spray, all other controllable variables being constant, is illustrated by representative records in figure 5.

Results obtained when Diesel fuel was repeatedly injected into a single, individual gas charge are presented in table II. Figure 6 comprises the corresponding records, taken with a gas temperature of 250° C. It is to be noted that these records do not correspond to consecutive injections.

The results obtained with benzene are presented in table III and figure 7. These tests were limited to the smaller weights because of the greater pressure changes per unit weight of liquid.

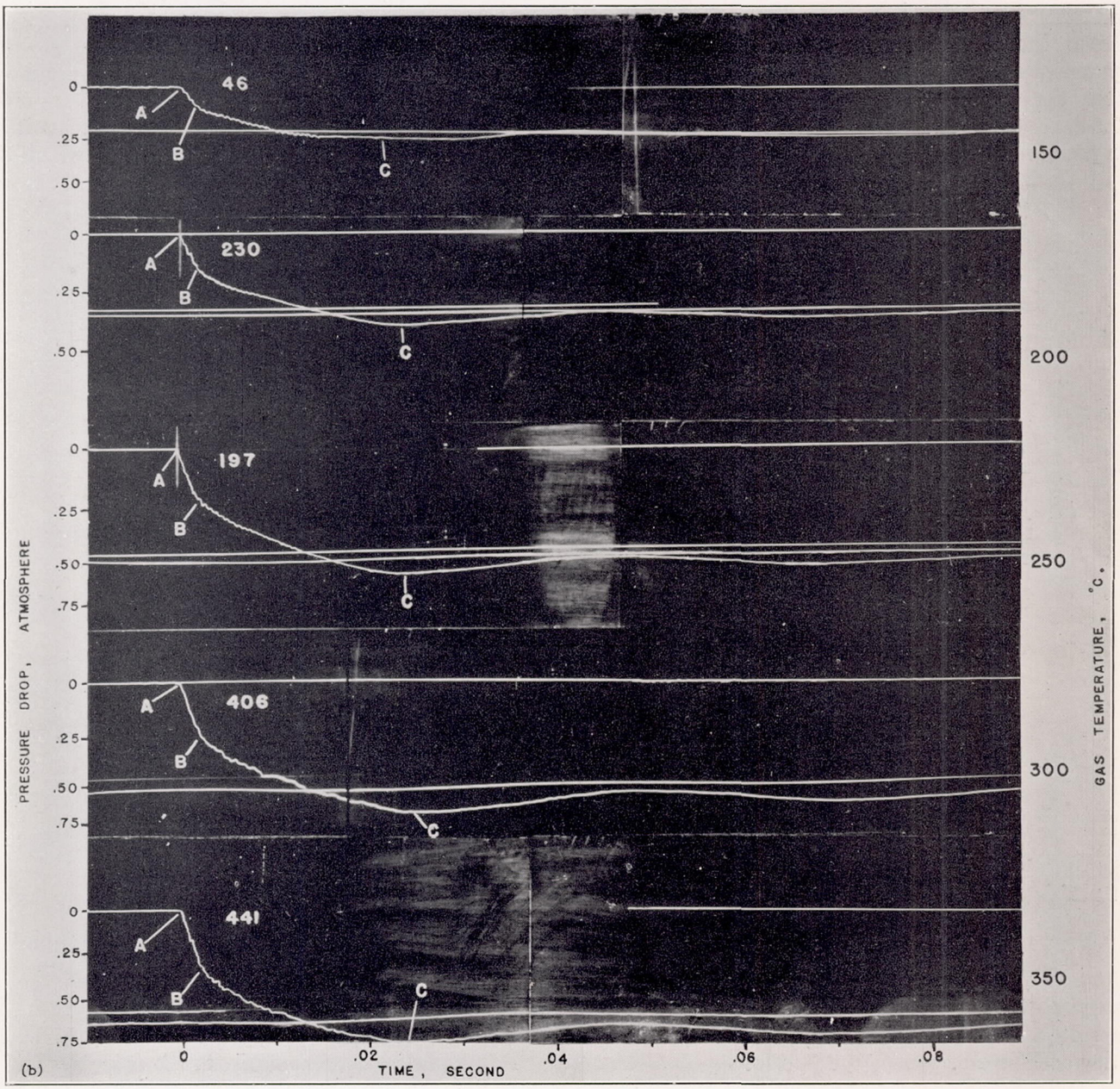
An inspection of the experimental records reveals two time intervals more or less clearly defined on all the pressure-time curves. Three characteristic points are designated on all the records reproduced: A, the point at which the pressure drop begins; B, the end of the initial pressure drop for which the rate was essentially constant; and C, the minimum pressure point. The start of injection corresponds, with one exception, to the vertical line appearing on some of the records and is coincident with the A points; i. e., the decrease in the gas pressure began immediately after the first part of the fuel charge entered the bomb. The one exception (record 295, fig. 5) was due to improper synchronization of the injection start and the timing spark. The A–B interval and the pressure drop associated with it are indicative of processes occurring immediately after the injection starts. This interval is therefore of primary interest with respect to compression-ignition



(a) Gas density, 4.73 grams per liter; gas-fuel ratio, 10.

FIGURE 4.—Variation of pressure drop with gas temperature. Diesel fuel; fuel weight, 0.284 gram.

engines. The whole A–C interval, on the contrary, is of no immediate interest in this respect and corresponds to the period within which heat is being abstracted from the gas phase at a rate greater than the rate of transfer from the bomb wall. The A–C interval is partial pressure of the vaporized fuel. Records representing this condition were not obtained as the relatively low rate of heat transfer from the bomb wall would have necessitated an extended deflection period for the diaphragm.



(b) Gas density, 14.19 grams per-liter; gas-fuel ratio, 30.

FIGURE 4.—Continued. Variation of pressure drop with gas temperature, Diesel fuel; fuel weight, 0.0284 gram.

influenced so little by most of the available variables that no theoretical basis for its approximate constancy is at present evident. Eventually, upon reestablishing thermal equilibrium, the pressure should increase beyond its initial value to an extent represented by the

Spray photographs shown in figure 8 illustrate the manner in which sprays from the 13-orifice and the 2-impinging-jets nozzles penetrate air at room temperature and a density of 14.19 grams per liter for an intermediate injection pressure.

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PRECISION OF RESULTS

The reproducibility of the experimental results depended upon the nonvariation of the fuel quantity and the indicator calibration. The maximum deviations in the observed data for apparently identical conditions amounted to roughly ±5 percent of the average values. The variation in fuel weights, for apparently identical injection pressures, was approximately the same for all weights and amounted to about ±3.5 percent of the actual weight for the lower injection pressures or to ±1 percent for the higher.

weight, prevented the use of the larger fuel weights. The objectionable feature of the shift arose from the fact that a given deflection before and after a particular test did not correspond to equivalent pressures. A possible error of perhaps ±5 percent may arise in this way; at 350° C. the error is undoubtedly greater.

When the data from the records were evaluated, some personal error was introduced, particularly for the A–B portion of the curve wherein the interval is more or less arbitrary and the distances on the record are often too small to be accurately measured. The magnitude of this uncertainty is shown in figure 9, for which the

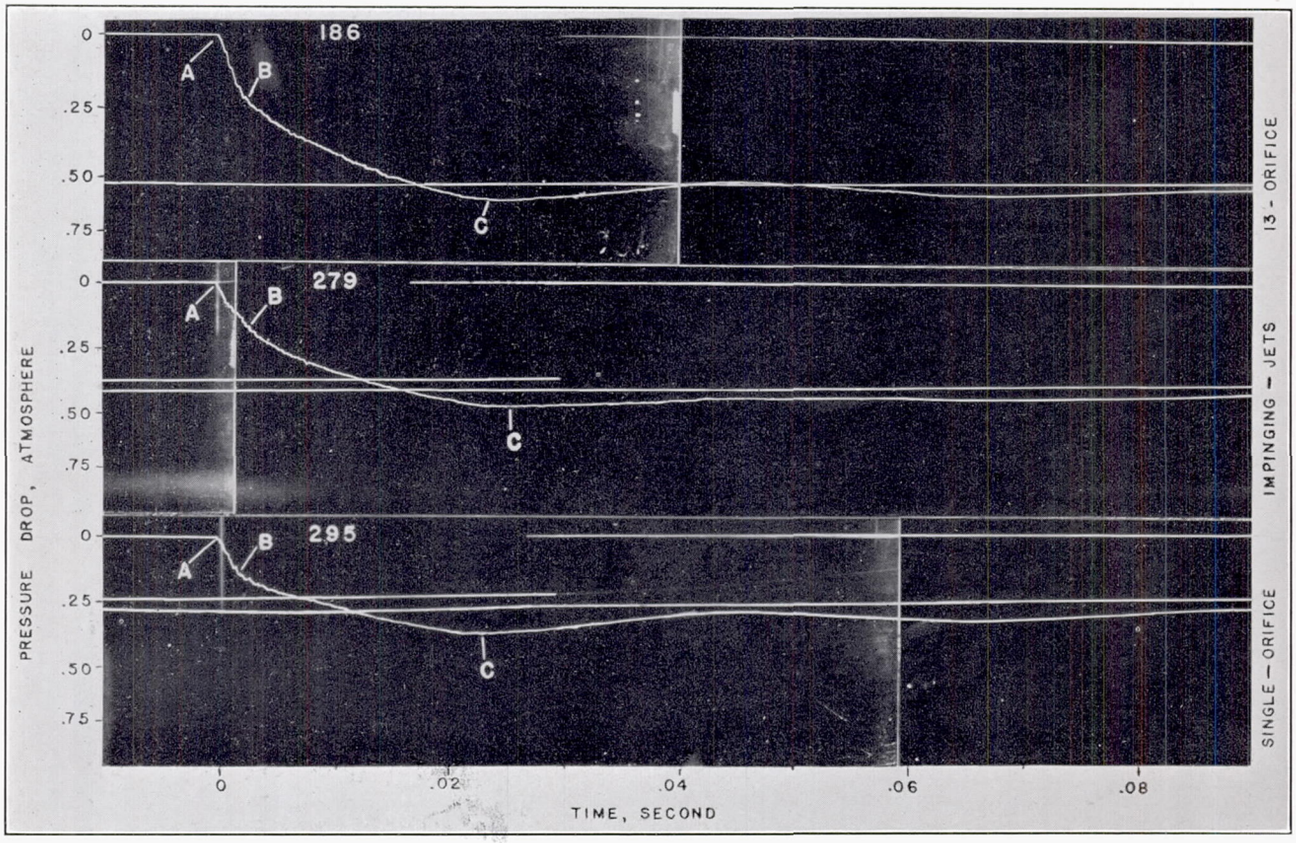


FIGURE 5.—Effect of nozzle design on pressure drop. Diesel fuel; fuel weight, 0.284 gram; gas-fuel ratio, 30; gas density, 14.19 grams per liter; gas temperature, 250° C.

At temperatures of 250° C. and above, the indicator showed a decided tendency to change its zero point as a result of creeping of the diaphragm, particularly during calibration when the deflection period was relatively great. The extent of this shift increased with the amount of deflection, the time of deflection, and the temperature. The deflection interval was diminished as much as possible during calibrations by a quick application and release of the gas pressure. The zero point immediately after deflection was taken as the proper basis for calibration in spite of its tendency in many cases to drift back toward its original position. At 350° C. this restoration was less evident and the shift assumed serious proportions. This fact, together with the increased deflection per unit fuel

data were taken by two observers from the same records. The individual deviations are rather great, but the mean curves seem to fit either set of data equally well. At 150° C. the records were so flat in the neighborhood of the minimum point that C was taken as the center of the flat portion of the curve. For the larger deflections the trace near the minimum point contained a wave of relatively low frequency. An average of the amplitudes of the first cycle was applied as a negative correction to compensate for this wave.

One other point of incidental interest is the change in fuel temperature as a result of the injection process. The passage of the fuel through the nozzle would ordinarily result in a small decrease in temperature on the basis of the Joule-Thomson effect (reference 24), assum-

ing the coefficient to be positive as for certain other hydrocarbons (reference 25). Qualitative experience indicates, however, that the net effect is a temperature increase due to friction in the orifice and the conversion of the kinetic energy of the spray into heat. The change is believed to be too small to be of any interest in the interpretation of the present results and will therefore be ignored.

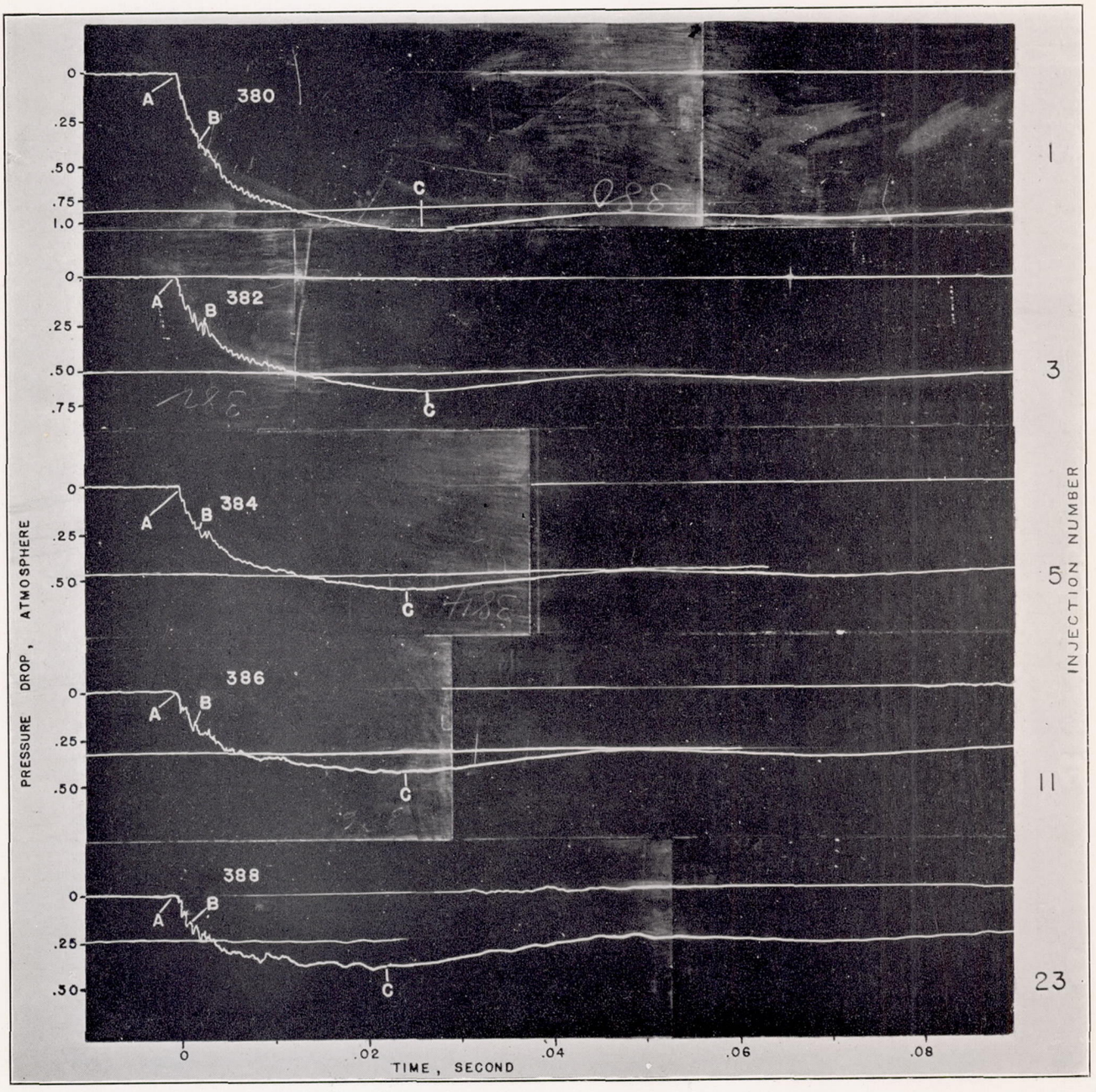


FIGURE 6.—Influence of fuel-vapor concentration, prior to injection, upon pressure drop. Diesel fuel; fuel weight per injection, 0.568 gram; gas density, 10.35 grams per liter; gas temperature, 250° C.

DISCUSSION

On the basis of diffusion and heat-transfer concepts the size of a droplet must influence its rate of heating and vaporization. Lee has shown (reference 20) that the degree of subdivision attainable with a hydraulic injection system under operating conditions approaches a practical limit. For the practical range of gas densities and injection pressures, however, it is impossible to vary the distribution of droplet sizes without at the same time varying the rate of spray penetration. This concomitant variation prevents the isolation of any effect that can be associated solely with the distribution of droplet sizes. In the subsequent discussion it is well to bear in mind that the same condition should be true of certain other quantities that may represent an aggregation of variables.

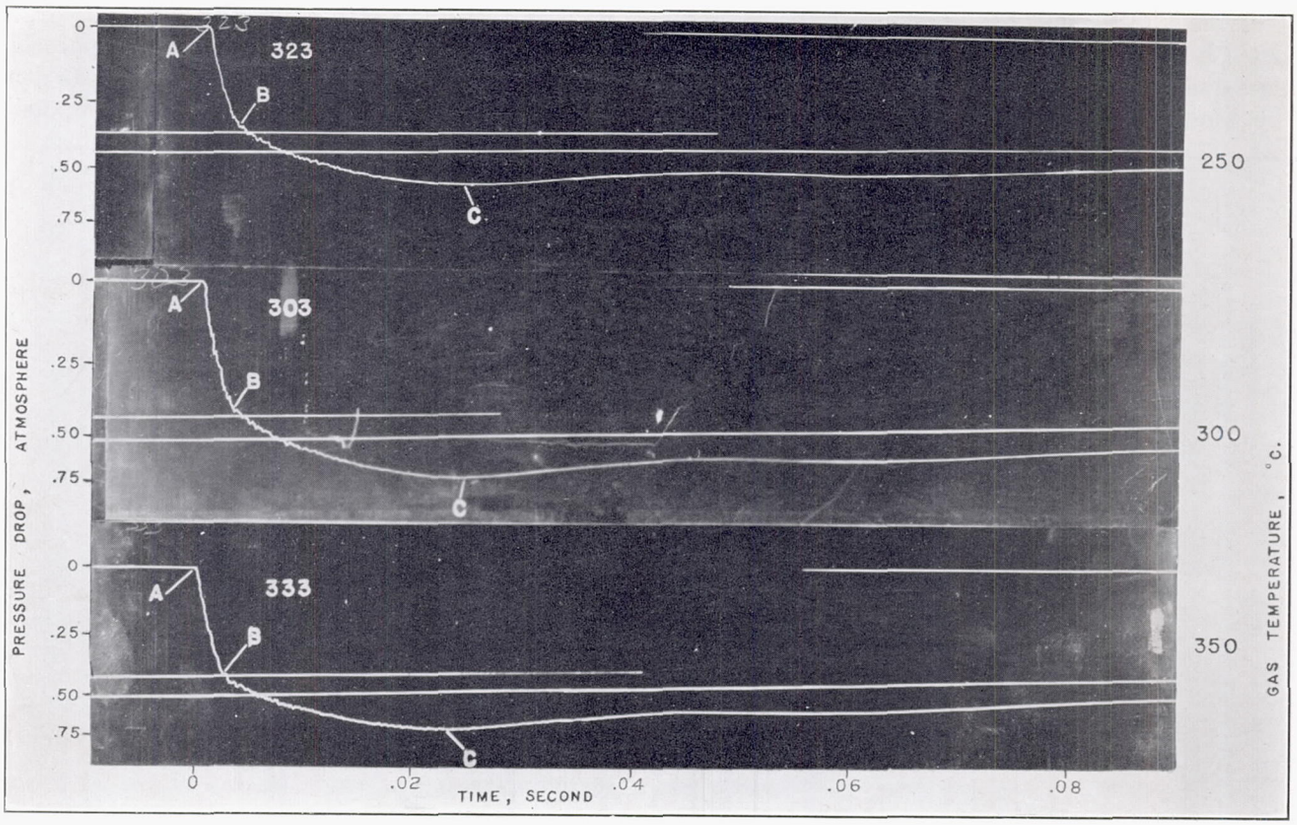


FIGURE 7.—Effect of gas temperature on pressure drop. Benzene as fuel; fuel weight, 0.284 gram; gas-fuel ratio, 10; gas density, 4.73 grams per liter.

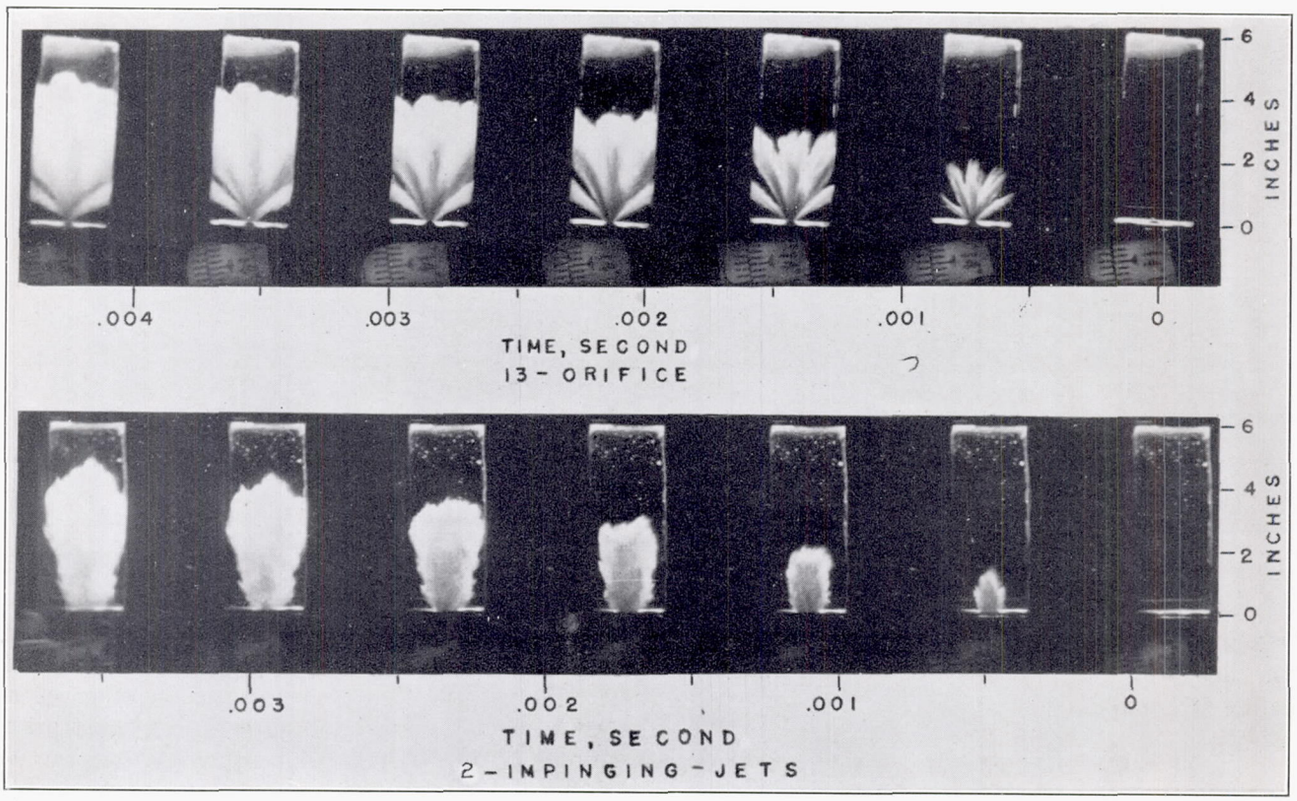


FIGURE 8.—Spray penetration. Gas density, 14.19 grams per liter; injection pressure, 5,800 pounds per square inch.

THE A–B INTERVAL

The A–B intervals correspond to the early part of the spray development for which the rate of heat transfer is essentially constant for a particular record. It is possible that this constancy is in some way associated with the approximately constant initial rate of spray-tip penetration (references 1 and 26). The magnitude of this interval is comparable with the ignition lag in compression-ignition engines. For this reason any conclusions based upon this interval are also applicable to such engines, provided that proper allowances are made for differences in chamber size and air temperature. The photographs shown in figure 8, together with more extensive penetration data (reference 1), show that this interval is essentially equivalent to the time (0.002 to 0.003 second) required by the sprays to traverse a distance of 4 inches, the approximate diameter of the bomb

This association of the moment of impingement with point B is supported by the fact that the interval decreases as the gas density decreases, i. e., as the penetration increases. (See table I, column 7.) On the contrary, the interval is not appreciably shorter for the single-orifice nozzle in spite of the greater penetration to be expected with it. The period is about the same for carbon dioxide as for nitrogen in contradistinction to the longer A–C interval with carbon dioxide. Increasing the fuel quantity increases the injection period by a maximum factor of 3, yet the interval remains essentially the same. The interval also proved to be independent of the fuel used.

Initial rate of heat transfer.—The magnitude of the initial rate of pressure drop, as shown by the particular pressure-time curve, is representative of the total rate of heat exchange between the gas and the fuel for the early part of the spray. The manner in which this initial rate is influenced by the temperature gradient between the gas and the fuel at two gas densities and several fuel weights is illustrated in figure 9. These initial slopes become more negative, i. e., the initial rate of heat transfer increases, as either the temperature difference or the fuel weight increases. Increasing the gas density decreases the numerical magnitude of the slope for a given fuel quantity but does not greatly alter the temperature dependence of the initial rate of pressure drop of the pressure-time curve: corresponding lines in figure 9 have roughly the same slope.

The increased density evidently decreases the effective transfer area in the early part of the spray as might be expected from the slower rate of spray development shown by the photographs reproduced in reference 1. The decrease cannot be attributed to a lower rate of heat transfer per unit area because the coefficient of heat conductivity should be nearly independent of density and the coefficient of heat transfer might be expected to increase with gas density (reference 27). Carbon dioxide gave rise to a greater rate of temperature drop than did nitrogen, even though its rate of pressure drop was smaller. This fact may be demonstrated by dividing the values of the initial slope in column 9 of tables I and III by their respective initial pressures, as outlined earlier in this paper. As the specific heats of nitrogen and carbon dioxide do not differ greatly on a weight basis, carbon dioxide must have given a greater initial rate of heat transfer. Since carbon dioxide has a lower coefficient of heat conductivity, it must give a greater effective heat-transfer area. The slopes for benzene (table III) are slightly greater than for Diesel fuel (table I) owing perhaps to a combination of the differences in the properties (molecular weight, specific heat, heat of vaporization, etc.) of the two fuels.

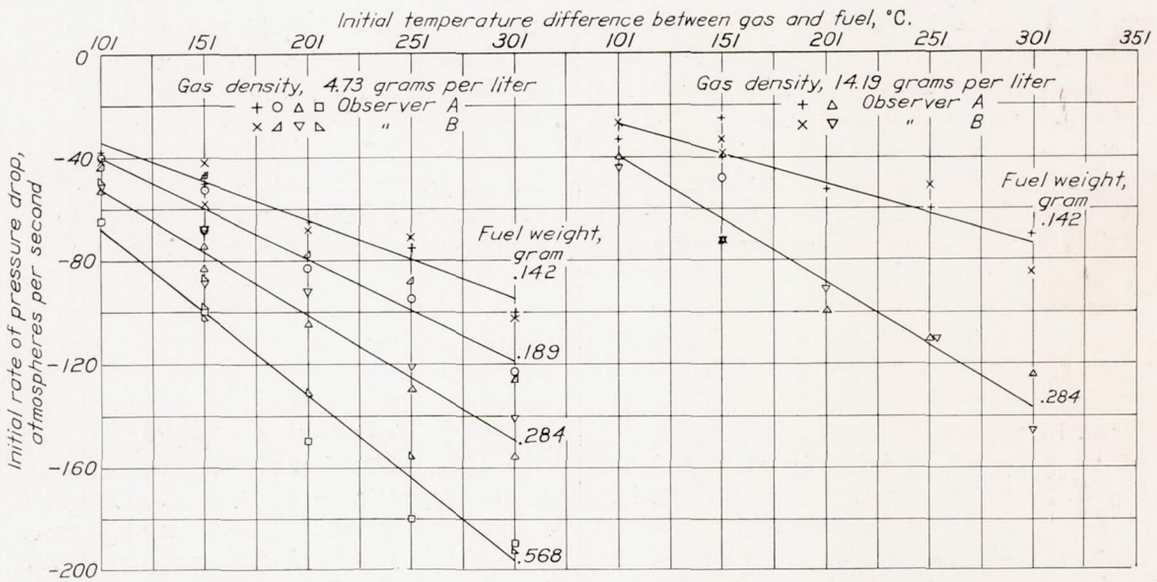


FIGURE 9.—Effect of gas temperature on initial rate of pressure drop at different gas-fuel ratios.

For the lowest density the impinging-jets nozzle gave a heat-transfer rate similar to the 13-orifice nozzle but at the highest density its rate was substantially less. The single-orifice nozzle gave a smaller rate at all densities. The maximum cylinder pressures obtained with similar nozzles and the N. A. C. A. combustion apparatus show the same trends, indicating that better initial mixing of fuel and air, together with the resulting improvement in heat transfer, occurs with the high-dispersion nozzles (reference 3). No information relevant to the effect of vapor concentration on the ignition lag can be obtained from such an engine study, presumably because all nozzles giving at least moderate fuel dispersion permit the optimum air-vapor mixture somewhere within the spray and thus give approximately the same ignition lag.

The contribution of radiation to the total heat-transfer rate can be shown to be negligible on the basis of the treatment given in an earlier section. If record 418 is considered to be typical of the others, the rate of pressure drop equivalent to the maximum rate of radiation that could occur is only 1 percent of the observed rate. It appears that radiation contributes little toward heating the fuel injected into an engine except for the possibility of unvaporized fuel becoming surrounded by a cloud of radiating combustion products. Even in this case, the conductive heat exchange can be shown to predominate if its rate per degree temperature difference remained constant and independent of the gas temperature to the extent indicated by the data in column 10 of table I.

Effect of temperature on initial heat transfer.—Straight lines seem to agree with the data plotted in figure 9 within the limits of the uncertainty involved and, moreover, such lines are in agreement with a rate of heat transfer directly proportional to the temperature difference. The fact that the lines are straight indicates that the gas temperature has little influence on spray development within the range employed (reference 28), measured in this case by the effective area available for heat transfer. This area appears to be constant for a given density and fuel weight; otherwise a compensating change in the heat-transfer coefficient must be assumed. There is no indication that the slopes of the lines of figure 9, and hence the corresponding heat-transfer coefficients, will assume different values at the higher temperatures attained in an engine. The extrapolation, however, is too great to be of more than qualitative interest. The mass flow of gas inherent in an engine (reference 4) would lead to greater effective transfer areas and thus increase the apparent rate of pressure decrease indicated in this figure.

The ratios of the initial slope values given in column 9 of tables I and III to the respective products of fuel weight and initial fuel-gas temperature difference give a fundamental basis for comparing the relative efficacy of the heat transfer in all cases for a given ambient gas. It follows from such ratios that the rate of heat transfer varies directly with the initial temperature difference, as stated earlier in connection with figure 9. Increasing the weight of Diesel fuel leads to considerable decrease in these values but with benzene the tendency is not so evident. This difference indicates that the effective heat-transfer area is more nearly proportional to the fuel weight for benzene than for Diesel fuel. Again, as with the initial slopes, these ratios are somewhat greater for benzene, but it is not known whether this situation arises from a greater heat requirement or from better spatial distribution of the spray. The latter seems most probable in view of the effect of fuel viscosity on the distribution of fuel within the spray (references 2 and 29).

Fuel vaporization.—The records reproduced in figure 6 show that some evaporation of the fuel occurs during the A–B interval. If all the heat transferred served merely to heat the liquid fuel, it is evident that the initial rate of heat transfer should not decrease as it does in these records. As more and more fuel is injected into the same gas charge, thermal equilibrium being reestablished before each injection, such a condition is approximated as the partial pressure of the vapor and the saturation pressure of the liquid approach one another. Certainly the relatively small molecular concentrations of vapor that produce the diminutions in initial heat-transfer rate evident even after a single injection can only be effective in the observed manner by retarding the evaporation of the fuel. These records show that the heat transferred to the vapor or to the fuel in effecting vaporization represents an appreciable part of the total heat transferred to an ordinary spray during the A–B interval. Rothrock and Waldron (reference 8) have presented conclusive evidence that considerable vaporization does occur in a high-speed engine but the rate, of course, is indeterminate as in the present case. The speed of the engine proved to be influential, presumably for two reasons: differences in mechanical mixing of the spray with the air, and certain changes in the thermal boundary conditions of the spray. Photographs in reference 30 of sprays injected into cold and heated air show a distinct decrease in the spray penetration with the hot air. It is quite probable that vaporization of the fuel within the spray envelope contributed to this decrease in addition to the changes in fuel temperature and air viscosity, which were cited in explanation of this phenomenon.

THE A–C INTERVAL

Effectiveness of heat transfer.—Even though the B–C portion of the A–C interval has no particular connection with engine operation, it does present some information of interest on the effectiveness of the heat transfer. This effectiveness is shown most readily by comparing with the actual pressure drop the calculated pressure drop that should take place if all the fuel had vaporized. The nearer the experimental value approaches the calculated value the greater the effective-

ness of the transfer. Calculated and observed pressure changes are plotted against the initial nitrogen (or air) pressure in figure 10 for several temperatures and a gas-fuel ratio of 20.

The disagreement between the calculated and observed pressure drops is very striking and is much too great to be associated with heat transferred from the bomb wall to the gas phase during the A–C interval, as evidenced by the slow rate of pressure rise after point C. A probable explanation is that a good fraction of the fuel struck the wall, deriving most of its heat therefrom. This assumption is supported by earlier observations that a definite pattern of the sprays could be seen on the bomb wall after certain explosion tests (reference 23) and particularly by the photographs in figure 8. At lower gas densities or with the single-orifice nozzle, the penetration should be greater (reference 1) and the time required to traverse the bomb somewhat shorter. In any case the sprays struck the bomb wall long before minimum pressure was attained.

In view of the discrepancy between the calculated and observed pressure changes it is rather surprising that the experimental pressure drops are directly proportional to the initial pressure. There is no particular reason for believing that the vapor left the wall in temperature equilibrium with it; i. e., that this vapor could abstract little or no heat from the gas phase, unless perhaps the mass motion of the gas was too slow to effect the removal of the vapor from the immediate neighborhood of the wall in the interval examined.

The ratio of observed to calculated pressure drop is indicative of the fraction of the total heat contributed by the gas phase. It follows from figure 10 that above 250° C. the fraction of the total heat contributed by the walls became relatively constant at all temperatures for a given density and a gas-fuel ratio of 20, indicating that a constant fraction of the fuel charge struck the wall at temperatures above 250° C., the gas density being almost noninfluential.

The total pressure drop subsequent to injection increases with initial temperature, fuel quantity, and to some extent with initial density, although in the higher range this latter change is not very evident. There is also a slight decrease in this drop (table I, section 7) with a moderate increase in fuel temperature, showing that in this case less total heat is transferred to the portion of the fuel charge that normally absorbs heat from the gas phase. With carbon dioxide as the ambient gas, the drop is less than that for nitrogen, but a consideration of the relative initial pressures shows that the corresponding temperature drops are of the same magnitude. This similarity might be expected because the spray development is about the same for a given density irrespective of the nature of the gas (reference 28) and, on a weight basis, the specific heat of carbon dioxide is not greatly different from that of nitrogen in this temperature range. For a given fuel weight benzene gives a greater drop than does the Diesel fuel, presumably owing to the greater heat required for vaporization. This presumption assumes that the same fraction of the fuel (benzene or Diesel fuel) fails to strike the wall under identical circumstances. The benzene tests also indicate that the surface temperature of the drops is well below the ambient-gas temperature; although the gas temperatures employed were near to or above the critical temperature of benzene, the fact that the A–C interval was about the same for benzene as for Diesel fuel indicates a droplet temperature much below the critical point.

Time to attain minimum pressure.—Small variations of the A–C interval are evident but, because of possible errors, these variations may not be real. In any case the variations cannot be associated with any primary variable. The interval is greatest for carbon dioxide, intermediate for air, and least for nitrogen; it increases with the fuel quantity for the lower but not for the higher weights; and there appears to be a slight increase with gas density. As the total pressure drop increases with an increase in the fuel weight and to some extent with an increase in gas density, it is conceivable that the latter trends arise from an "overshooting" of the true decrease in pressure because of the increased amplitude of the wave evident after point C. The records for benzene, however, fail to show such trends.

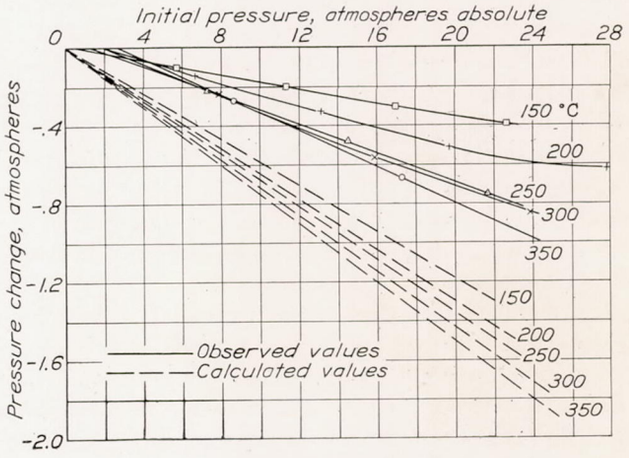


FIGURE 10.—Comparison of calculated and observed pressure drops at various temperatures.

In view of the wide variation of the fraction of the fuel that strikes the bomb wall with varying fuel weights and given gas density, the minimum point cannot be logically associated with the moment of complete evaporation of the fuel on the wall. This contention is further substantiated by the failure of benzene to give a shorter interval; its greater volatility should enable it to evaporate more rapidly from the bomb surface. It has previously been shown that nonuniformity of the gas-vapor mixture exists for at least 0.06 second after injection (reference 23). An attempt was made to mix the charge with a 4-blade fan driven at 7,000 r. p. m. but, as the A–C interval corresponded to only two revolutions of the fan, it is not surprising

that the interval was unaltered. Since the rates of heat transfer from the wall and to the fuel are equal at C, it would seem that the interval should depend upon the nonuniformity of the mixture, which in turn should be dependent upon the injected fuel weight and the gas density. Actually, the interval is practically independent of both variables.

CONCLUSIONS

1. The injection of liquid fuel into a heated and compressed gas has furnished data on the initial rate of heat exchange between the ambient gas and the fuel. The actual rates of vaporization were indeterminate, but it is shown that vaporization began immediately after injection started. The same situation must also be true for engines.

2. For given experimental conditions, the initial rate of heat transfer was essentially constant during the time required for the spray to traverse the bomb. This initial rate was found to be proportional to the initial temperature difference between the fuel and the gas. The total heat transferred in engines must be greater owing to the greater initial temperature difference.

3. The initial heat-transfer period was approximately constant (0.0020 ± 0.0005 second) for the 13-orifice, 2-impinging-jets, and single-orifice nozzles tested and also for benzene and Diesel fuel, which have quite different volatilities and viscosities.

4. At the temperatures investigated the transfer of heat by radiation was negligible as compared with that transferred by conduction. This situation must also exist in an engine until the start of flame combustion.

5. The efficacy with which heat transfer took place decreased considerably with increasing fuel quantity at all densities and temperatures investigated.

6. Under all conditions a good fraction of the total heat absorbed after the spray had traversed the bomb must have occurred at the bomb wall.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *August 25, 1936.*

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TABLE I

PRESSURE CHANGE ASSOCIATED WITH HEAT TRANSFER TO DIESEL FUEL

1	2		3		4	5	6	7	8	9	10
Record number	Initial gas pressure		Gas density		Gas-fuel ratio	Fuel weight (gram)	Pressure drop (atmosphere)	Interval A to B (second)	Interval A to C (second)	Initial slope (atmospheres per second)	Initial slope per gram per ° C. difference $\left(\frac{\text{atmospheres}}{\text{second gram °C.}}\right)$
	Atmospheres, absolute	Pounds per square inch (gage)	Grams per liter	Pounds per cubic foot							
1. AIR AT 150° C. (302° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
17	5.67	69	4.73	0.296	20	0.142	0.10	0.0013	0.023	−38	−2.7
34					15	.189	.12	.0015	.023	−40	−2.1
35, 19					10	.284	.15	.0015	.023	−53	−1.8
36, 20					5	.568	.26	.0020	.023	−65	−1.1
37	11.34	152	9.46	.592	40	.142	.12	.0017	.023	−29	−2.0
38					30	.189	.16	.0020	.023	−40	−2.1
39					20	.284	.20	.0020	.023	−50	−1.7
40					15	.378	.25	.0020	.023	−60	−1.6
23, 41					10	.568	.36	.0020	.023	−65	−1.1
44	17.01	235	14.19	.888	60	.142	.12	.0015	.023	−33	−2.3
45					45	.189	.16	.0020	.025	−30	−1.6
46					30	.284	.22	.0020	.025	−40	−1.4
26					20	.426	.30	.0020	.025	−55	−1.3
27					15	.568	.39	.0020	.027	−55	−1.0
50	22.68	319	18.93	1.184	40	.284	.23	.0020	.030	−40	−1.4
49					20	.568	.38	.0020	.027	−50	−.9
2. AIR AT 200° C. (392° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
73	6.34	79	4.73	0.296	20	0.142	0.15	0.0015	0.023	−47	−2.2
56					15	.189	.18	.0015	.023	−68	−2.4
75					10	.284	.25	.0020	.023	−75	−1.7
76					5	.568	.46	.0015	.023	−100	−1.2
77	12.68	172	9.46	.592	40	.142	.18	.0020	.027	−35	−1.6
78					20	.284	.32	.0020	.027	−70	−1.6
81, 79					15	.378	.41	.0025	.027	−72	−1.3
80					10	.568	.61	.0025	.027	−88	−1.0
82	19.02	265	14.19	.888	60	.142	.18	.0020	.029	−25	−1.2
83					30	.284	.34	.0025	.029	−48	−1.1
84					20	.426	.48	.0025	.029	−60	−.93
85					15	.568	.61	.0025	.030	−72	−.84
86	25.36	358	18.93	1.184	80	.142	.16	.0020	.029	−20	−.93
89					40	.284	.31	.0020	.030	−50	−1.2
88					20	.568	.57	.0020	.030	−65	−.76
3. NITROGEN AT 200° C. (392° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
202	6.56	82	4.73	0.296	20	0.142	0.14	0.0015	0.023	−50	−2.3
222					15	.189	.17	.0020	.023	−52	−1.8
223					10	.284	.26	.0018	.023	−83	−1.9
205					5	.568	.48	.0025	.023	−88	−1.0
225	13.12	178	9.46	.592	40	.142	.20	.0015	.023	−53	−2.5
207					20	.284	.33	.0020	.023	−80	−1.9
227					15	.378	.45	.0020	.023	−100	−1.8
209					10	.568	.65	.0020	.023	−110	−1.3
211	19.68	275	14.19	.888	60	.142	.21	.0020	.024	−40	−1.9
230					30	.284	.37	.0022	.024	−73	−1.7
213					20	.426	.51	.0025	.023	−88	−1.4
214					15	.568	.67	.0025	.025	−88	−1.0
215	26.24	371	18.93	1.184	80	.142	.18	.0020	.023	−30	−1.4
234					40	.284	.37	.0020	.024	−60	−1.4
235					27	.426	.51	.0025	.023	−72	−1.1
236					20	.568	.63	.0025	.026	−80	−.93
4. NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
177	7.25	92	4.73	0.296	20	0.142	0.22	0.0015	0.023	−65	−2.3
178					15	.189	.26	.0018	.023	−83	−2.2
191					10	.284	.37	.0020	.023	−115	−2.0
192					5	.568	.69	.0020	.023	−150	−1.3
193, 181	14.50	199	9.46	.592	40	.142	.27	.0018	.024	−55	−1.9
182, 194					20	.284	.48	.0025	.023	−96	−1.7
183, 195					15	.378	.65	.0025	.024	−124	−1.6
184					10	.568		.0025		−140	−1.2
196	21.75	305	14.19	.888	60	.142	.30	.0015	.025	−53	−1.9
197, 186					30	.284	.52	.0020	.024	−100	−1.8
198, 187					20	.426	.75	.0025	.025	−100	−1.2
188					15	.568		.0025		−120	−1.1
5. NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 82° C.; 13-ORIFICE NOZZLE											
255	7.25	92	4.73	0.296	20	0.142	0.20	0.0020	0.023	−60	−2.5
239					15	.189	.23	.0020	.023	−70	−2.2
257					10	.284	.36	.0020	.023	−105	−2.2
241, 258					5	.568	.65	.0020	.023	−140	−1.5
242	14.50	199	9.46	.592	40	.142	.27	.0017	.023	−65	−2.7
260, 243					20	.284	.47	.0022	.023	−100	−2.1
261, 244					15	.378	.60	.0025	.024	−112	−1.8
262, 245					10	.568	.83	.0025	.025	−124	−1.3
246	21.75	305	14.19	.888	60	.142	.27	.0020	.025	−50	−2.1
247, 264					30	.284	.50	.0022	.025	−91	−1.9
265					20	.426	.66	.0025	.025	−104	−1.5
266					15	.568	.86	.0025	.025	−104	−1.1

TABLE I—Continued

PRESSURE CHANGE ASSOCIATED WITH HEAT TRANSFER TO DIESEL FUEL

1	2		3		4	5	6	7	8	9	10
Record number	Initial gas pressure		Gas density		Gas-fuel ratio	Fuel weight (gram)	Pressure drop (atmosphere)	Interval A to B (second)	Interval A to C (second)	Initial slope (atmospheres per second)	Initial slope per gram per ° C. difference $\left(\frac{\text{atmospheres}}{\text{second gram ° C.}}\right)$
	Atmospheres absolute	Pounds per square inch (gage)	Grams per liter	Pounds per cubic foot							
6. NITROGEN AT 300° C. (573° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
394	7.94	102	4.73	0.296	20	0.142	0.24	0.0020	0.024	−75	−2.1
398					15	.189	.27	.0020	.023	−95	−2.0
396					10	.284	.42	.0020	.023	−130	−1.8
399					5	.568	.86	.0020	.024	−180	−1.3
404	15.88	219	9.46	.592	40	.142	.29	.0017	.025	−82	−2.3
401					20	.284	.56	.0020	.025	−135	−1.9
402					15	.378	.74	.0025	.025	−140	−1.5
403					10	.568		.0025		−160	−1.1
405	23.82	335	14.19	.888	60	.142	.32	.0015	.026	−60	−1.7
406					30	.284	.61	.0020	.026	−110	−1.6
408					22.5	.378	.78	.0025	.026	−112	−1.2
407					20	.426		.0025		−132	−.93
7. NITROGEN AT 350° C. (662° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
418	8.63	112	4.73	0.296	20	0.142	0.27	0.0017	0.023	−100	−2.3
415					15	.189	.35	.0017	.025	−123	−2.2
416					10	.284	.52	.0020	.024	−156	−1.8
417					5	.568	.92	.0025	.025	−190	−1.1
420	17.26	239	9.46	.592	40	.142	.38	.0018	.025	−94	−2.2
437					30	.189	.47	.0025	.025	−96	−1.7
438					20	.284	.67	.0025	.025	−132	−1.5
439	25.89	366	14.19	.888	60	.142	.40	.0020	.026	−70	−1.6
440					45	.189	.50	.0020	.026	−95	−1.7
441					30	.284	.71	.0025	.025	−124	−1.5
8. NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; IMPINGING-JETS NOZZLE											
270	7.25	92	4.73	0.296	20	0.142	0.25	0.0020	0.023	−60	−2.1
271					15	.189	.29	.0020	.023	−80	−2.1
272					10	.284	.37	.0020	.022	−110	−1.9
273					5	.568	.62	.0020	.023	−155	−1.4
274	14.50	199	9.46	.592	40	.142	.28	.0025	.024	−48	−1.7
275					20	.284	.45	.0025	.025	−80	−1.4
276					15	.378	.57	.0025	.024	−100	−1.3
277					10	.568	.74	.0025	.025	−116	−1.0
278	21.75	305	14.19	.888	60	.142	.29	.0022	.024	−41	−1.4
279					30	.284	.44	.0025	.026	−64	−1.1
280					20	.426	.63	.0025	.027	−92	−1.1
281					15	.568	.76	.0025	.027	−100	−.88
9. NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; SINGLE-ORIFICE NOZZLE											
286	7.25	92	4.73	0.296	20	0.142	0.10	0.0015	0.023	−33	−1.2
287					15	.189	.15	.0025	.022	−44	−1.2
288					10	.284	.22	.0020	.023	−70	−1.2
289					5	.568	.43	.0020	.020	−110	−.97
290	14.50	199	9.46	.592	40	.142	.16	.0020	.023	−40	−1.4
291					20	.284	.29	.0020	.023	−65	−1.1
292					15	.378	.40	.0020	.022	−95	−1.2
293					10	.568	.53	.0025	.022	−104	−.91
294	21.75	305	14.19	.888	60	.142	.20	.0020	.024	−45	−1.6
295					30	.284	.33	.0020	.023	−65	−1.1
296					20	.426	.51	.0025	.025	−88	−1.0
297					15	.568		.0025		−96	−.84
10. CARBON DIOXIDE AT 200° C. (392° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
131	4.18	47	4.73	0.296	20	0.142	0.09	0.0012	0.030	−42	−2.0
91					15	.189	.11	.0015	.035	−47	−1.6
114					10	.284	1.6	.0015	.030	−67	−1.6
115					5	.568	3.0	.0015	.030	−80	−.93
95	8.36	108	9.46	.592	40	.142	.11	.0015	.035	−33	−1.5
117					20	.284	.22	.0020	.030	−55	−1.3
97					15	.378	.27	.0020	.030	−60	−1.0
119					10	.568	.41	.0020	.032	−70	−.82
100	12.54	170	14.19	.888	60	.142	.12	.0015	.030	−27	−1.3
121					30	.284	.24	.0020	.035	−50	−1.2
122					20	.426	.34	.0020	.035	−70	−1.1
123					15	.568	.44	.0020	.035	−70	−.82
125	16.72	231	18.93	1.184	80	.142	.12	.0015	.037	−27	−1.3
126					40	.284	.25	.0020	.037	−40	−.93
127					27	.426	.33	.0020	.037	−55	−.85
128					20	.568	.44	.0020	.038	−55	−.64
11. CARBON DIOXIDE AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
158	4.62	53	4.73	0.296	20	0.142	0.12	0.0015	0.030	−50	−1.7
159					15	.189	.16	.0020	.030	−55	−1.4
160					10	.284	.22	.0015	.030	−100	−1.8
161					5	.568	.44	.0020	.030	−100	−.88
162	9.24	121	9.46	.592	40	.142	.18	.0015	.030	−53	−1.9
163					20	.284	.33	.0020	.031	−90	−1.6
164					15	.378	.44	.0020	.031	−100	−1.3
165					10	.568	.65	.0020	.030	−120	−1.0
166	13.86	189	14.19	.888	60	.142	.21	.0016	.032	−50	−1.7
167					30	.284	.37	.0020	.031	−90	−1.6
168					20	.426	.52	.0020	.031	−100	−1.2
169					15	.568	.68	.0025	.033	−100	−.88
170	18.48	257	18.93	1.184	80	.142	.21	.0015	.033	−40	−1.4
171					40	.284	.39	.0020	.033	−75	−1.3
172					27	.426	.54	.0020	.033	−100	−1.2
173					20	.568	.69	.0020	.035	−100	−.88

TABLE II

EFFECT OF FUEL VAPOR ON PRESSURE CHANGE FOR DIESEL FUEL

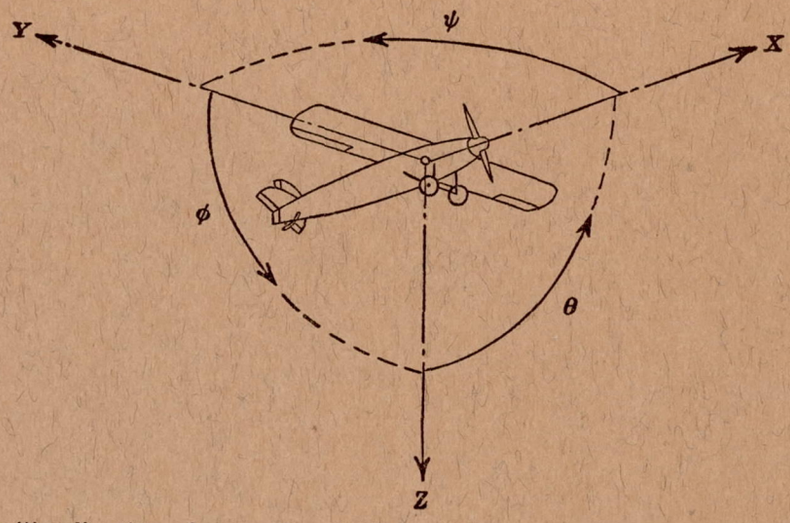
1	2		3	4	5	6	7	8	9
Record	Initial gas pressure: Atmospheres absolute (approx.)	Initial gas pressure: Pounds per square inch (gage)	Fuel quantity injected (gram)	Injection	Fuel in bomb before injecting (grams)	Pressure drop A to C (atmosphere)	Interval A to B (second)	Interval A to C (second)	Initial slope (atmospheres per second)
NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE									
380	15.88	219	0.568	1	0.000	0.94	0.0025	0.025	−156
381			.568	2	.568	.70	.0020	.025	−140
382			.568	3	1.14	.57	.0025	.025	−104
383			.568	4	1.70	.57	.0020	.025	−105
384			.568	5	2.27	.51	.0020	.025	−105
385	to	to	.568	8	3.98	.42	.0025	.025	−80
386			.568	11	5.68	.39	.0020	.025	−90
387			.568	17	9.09	.37	.0020	.025	−90
388			.568	23	12.5	.33	.0020	.023	−90
389	16.57	229	.568	34	18.7	.31	.0020	.023	−80
NITROGEN AT 350° C. (662° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE									
446	17.26	239	0.284	1	0.000	0.63	0.0025	0.023	−148
447	to	to	.284	5	1.14	.46	.0022	.024	−95
448			.284	10	2.56	.29	.0025	.025	−56
449	18.68	260	.284	15	3.98	.22	.0020	.024	−55

TABLE III

PRESSURE CHANGE ASSOCIATED WITH HEAT TRANSFER TO BENZENE

1	2		3		4	5	6	7	8	9	10
Record number	Initial gas pressure: Atmospheres absolute	Initial gas pressure: Pounds per square inch (gage)	Gas density: Grams per liter	Gas density: Pounds per cubic foot	Gas-fuel ratio	Fuel weight (gram)	Pressure drop (atmosphere)	Interval A to B (second)	Interval A to C (second)	Initial slope (atmospheres per second)	Initial slope per gram per ° C. difference $\left(\frac{\text{atmospheres}}{\text{second-gram °C.}}\right)$
1. NITROGEN AT 250° C. (482° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
315	7.25	92	4.73	0.296	20	0.142	0.30	0.0020	0.025	−85	−3.0
316					15	.189	.35	.0020	.024	−100	−2.6
317, 323					10	.284	.54	.0025	.023	−124	−2.2
318	14.50	199	9.46	.592	40	.142	.33	.0025	.025	−64	−2.2
319					30	.189	.40	.0020	.025	−95	−2.5
320					20	.284	.62	.0025	.024	−124	−2.2
2. NITROGEN AT 300° C. (572° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
301	7.94	102	4.73	0.296	20	0.142	0.36	0.0020	0.023	−85	−2.4
302					15	.189	.42	.0020	.025	−110	−2.3
303					10	.284	.64	.6025	.024	−144	−2.0
305	15.88	219	9.46	.592	40	.142	.39	.0020	.025	−90	−2.5
306					30	.189	.48	.0025	.024	−92	−1.9
307					20	.284	.76	.0025	.024	−140	−2.0
3. NITROGEN AT 350° C. (662° F.); FUEL TEMPERATURE, 49° C.; 13-ORIFICE NOZZLE											
331	8.63	112	4.73	0.296	20	0.142	0.37	0.0020	0.024	−105	−2.5
332					15	.189	.45	.0025	.024	−112	−2.0
333					10	.284	.69	.0025	.023	−172	−2.0
334	17.26	239	9.46	.592	40	.142	.43	.0025	.024	−92	−2.2
335					30	.189	.56	.0025	.023	−112	−2.0
336					20	.284	.85	.0025	.024	−172	−2.0

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Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$
P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h.
1 lb. = 0.4536 kg
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.